An Examination of Runoff Water Quality and Nutrient Export from a Forested Watershed Fertilized with Biosolids

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Introduction

Applying biosolids to both low and high quality sites in the Pacific Northwest increases the growth and size of Douglas fir (Henry et al., 1994). Thousands of acres of timber lands are currently excluded from biosolids fertilization due to existing guidelines that suggest applications be limited to terrain with slopes less than 30% (WDOE, 1996). Generally, slopes exceeding 30% are found on forested sites, and this is certainly the case within a region known as the Mountains to Sound Greenway (MTSG) between Seattle and Snoqualmie Pass.

Part of the MTSG program involves using biosolids for forest fertilization and biosolids compost for disturbed land reclamation and restoration, i.e., stabilization of steep slopes and abandonment of logging roads. Biosolids is used as an organic fertilizer, as it contains high concentrations of nitrogen (N) (6–7%) and phosphorus (P) (2–3%) on a dry weight basis. A concern within the MTSG is water quality protection and enhancement. One of the largest surface water receiving bodies is Lake Sammamish and it is P-limited. Dissolved and labile P entering the lake are both available for uptake, and high total lake P concentrations cause toxic algae blooms.

Experimental Basis and Objectives

Few studies consider whole-watershed water quality responses to biosolids fertilization, and no studies consider the application of dewatered biosolids. Metro (1986) examined water quality in ephemeral streams draining treated and control watersheds at the University of Washington's Pack Forest following application of liquid biosolids at a rate of 45 Mg ha^{-1}. Researchers used a 15-meter buffer from ephemeral streams draining the watersheds and found no significant difference in organic or mineral forms of N and P between the two watersheds. Kimmins et al. (1991) applied liquid digested biosolids to a 3.58 ha area within the East Creek Watershed in British Columbia and used an extensive network of stream monitoring to assess water quality. Concentrations of total-N, NO_3^--N, NH_3-N, and total and PO_4-P in East Creek and ephemeral drainages were almost equal to or below pre-biosolids application levels. Stream data included the evaluation of a 100-year storm that occurred within one month following biosolids application.

One of the unknowns regarding the use of biosolids within steep, forested watersheds is when stream water quality is most vulnerable to fertilization effects. Intuitively, the critical time to assess whether or not biosolids will move from a particular site is during periods of prolonged rainfall. The duration of Pacific Northwest storms is longest in the late autumn and winter months, with intensity highly variable; rain-on-snow events can and do produce substantial runoff hydrographs in streams. The experimental design discussed here is based on quantifying the concentrations and export of nutrients from a headwater watershed under runoff event flow conditions. The assumption is that if mobile constituents in biosolids are to move from a site, it would occur soon after application (as decomposition is still low) and it would occur under heavy rainfall conditions during the winter when soil moisture content is high.

Alternatively, following a winter application biosolids decomposes and releases nutrients through mineralization. Depending on the extent of uptake and soil immobilization, this process generally elevates the concentration of nutrients in the soil solution. This could create a situation in the autumn and early winter where available P or N production has exceeded uptake and the remaining P or N not taken up or immobilized by microbes could be lost to stream water during runoff events. A pattern of

seasonal increases and decreases in stream water nutrient concentrations has been observed in the Pacific Northwest and elsewhere (Edmonds et al., 1995; Feller, 1979; Vitousek and Reiners, 1975; Stoddard, 1994). This pattern depends on several factors including dominant vegetation, soil characteristics, and rainfall (and snowfall) amounts.

The objective of this study is to quantify the pattern and extent of P and N export during runoff events before and after biosolids application. In addition to the possible influence of biosolids, several other factors controlling stream water nutrient concentrations and export may operate within the watershed studied including management impacts such as thinning, seasonal changes in vegetation and soil nutrient status, and soil mineral weathering.

Study Site Characteristics

The 27 Creek Watershed is located at the University of Washington's 1720-ha Charles Lathrop Pack Demonstration Forest. Pack Forest is at the base of the Cascade foothills about 110 km south of Seattle. Dominant vegetation on the forest is second growth Douglas fir with some western hemlock, western red cedar and red alder. The climate is typical maritime, with relatively dry summers, wet winters, and moderate temperatures throughout the year. Annual precipitation is about 120 cm, with approximately 50% falling in the period of October through January. Rainfall during the period of July through August is usually less than 12 cm, often resulting in drought-like conditions on well drained soils. For normal temperatures and precipitation, evapotranspiration is estimated between 38 to 56 cm annually.

Watershed Description

The study site is a 21.4-ha headwater watershed and is drained by a first-order perennial stream (27 Creek). The watershed ranges between 420 and 600 meters elevation, with a northwesterly aspect (Figure 1). Topography is steep, with some slopes exceeding 60%. Nearly all of the watershed was clear-cut in 1982 and replanted the following year, and it currently consists of 15-year-old second growth Douglas fir intermixed with naturally regenerated western hemlock and red alder. Most of the watershed was pre-commercially thinned in March and April 1996; and felled trees were left in place.

Watershed Soils

Soil within the 27 Creek Watershed was formed from weathered andesite and basalt and is mapped as the Wilkensen soil series (fine-loamy, mixed mesic Vitrandic Haploxeralfs). Along the 27 Creek corridor, soils have characteristics of the Scamman series, a poorly drained clayey glacial till (fine, mixed, mesic Aeric Glossaqualfs). Watershed soil chemical characteristics are shown in Table 1.

Table 1. 27 Creek watershed and King County biosolids chemical composition.

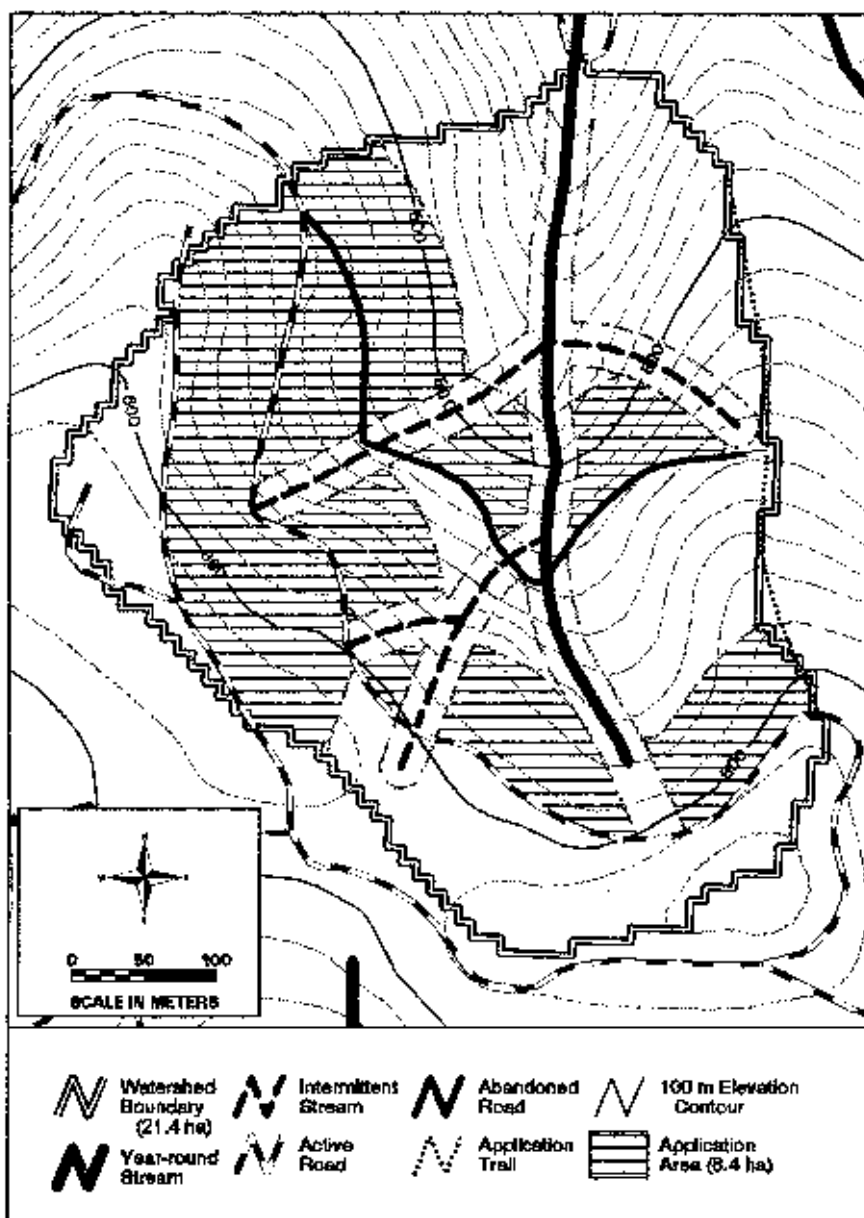|	NH_4^+-N	NO_3^--N	N	P	C	pH
	mg kg^{-1}		%			
27 Creek soil	22	6	0.13	0.03	3	4.2
King Co. biosolids	11200	11	7	2.5	34	8.7

Figure 1. 27 Creek Watershed, Pack Forest, Washington.

Watershed Hydrology

Flow rates in 27 Creek are seasonally influenced and highly responsive to rainfall amount and duration.
During wet weather months (October through April), flow rates vary between 75 and 10,000 L min^{-1}. The
highest flow rate recorded to date followed a rain-on-snow event between December 26 and 29, 1996.

During dry months, flow in the Creek has been recorded as low as 9 L min^{-1}. The Creek hydrograph
during a runoff event generally follows the pattern of a steep rise (time to peak usually less than 12 hours,
short peak duration of one to eight hours, and prolonged falling limb lasting two days or more).

Materials and Methods

Composition of Biosolids

Anaerobically digested, dewatered (20% solids) biosolids from King County's Renton Wastewater Treatment Plant was used; its chemical composition is shown in Table 1. Biosolids were applied to 8.4 of 21.4 hectares of the watershed during the third week of January 1997 and the first week of May 1997 to the hatched areas shown in Figure 1 at a rate of 13.5 Mg ha^{-1}.

27 Creek Flow Measurement and Water Quality Sampling

Automated flow recording and water sample collection devices were used to measure 27 Creek flow rate and to collect water samples during several runoff events before and after biosolids application. From November 1995 until present, water samples have been removed at least once a month by taking a grab sample at a single point in the Creek, followed by analysis for total P and total N. Beginning in October 1996, rainfall events causing a substantial rise in the stream hydrograph initiated automatic water sampling. After sampler initiation, water samples remained in the automatic sampler on ice until removal and transport to the King County Water and Land Resources Division Environmental Laboratory.

Analytical Methods

Total N and P as well as PO_4-P, NH_3-N, NO_3^--N were determined using standard methods for the examination of water (Standard Methods for the Examination of Water and Wastewater, 18th ed.). Biologically available P (BAP) was determined by filtering a known volume of creek water (0.45μm filter) and analyzing the extract for orthophosphate (Standard Methods for the Examination of Water and Wastewater, 18th ed., 4500-P, F). The material caught on the filter paper is extracted in a dilute sodium hydroxide/sodium chloride solution overnight, neutralized, filtered, and analyzed for orthophosphate. The sum of both determinations is BAP.

Soil and biosolids NH_4^+-N and NO_3^--N were extracted using 2.0 M KCl, then analyzed on a Technicon Autoanalyzer (Technicon Industrial Method No. 158-71W, 1977). Total N and C were determined by dry combustion (Perkin-Elmer CHN Analyzer Model 2400). Total P was determined using a HNO_3-H_2O_2-HCl acid digestion (EPA Standard Method 3050) and inductively coupled argon plasma spectroscopy (EPA Standard Method 6010. ICP; Thermo Jarrel Ash ICAP 61E, Thermo Jarrel Ash, Franklin, MA). Soil and biosolids pH were determined using a VFR model 3000 pH meter. A 1:2 soil/biosolids-distilled deionized water ratio was used with an equilibration time of 30 minutes before pH measurement.

Results and Discussion

Background Water Quality

Total N and P concentrations in 27 Creek between November 1995 and January 1998 are shown in Figure 2. Total P concentrations vary little, from 0.05 to 0.1 mg L^{-1}, while total N fluctuates much more, between 0.1 and 1. 5 mg L^{-1}. Total N concentrations in 27 Creek are higher after biosolids application as expected and seasonal fluctuations are evident, with the highest N concentrations recorded during late autumn. Background total P concentrations do not appear to be strongly influenced by seasonal changes or by biosolids application.
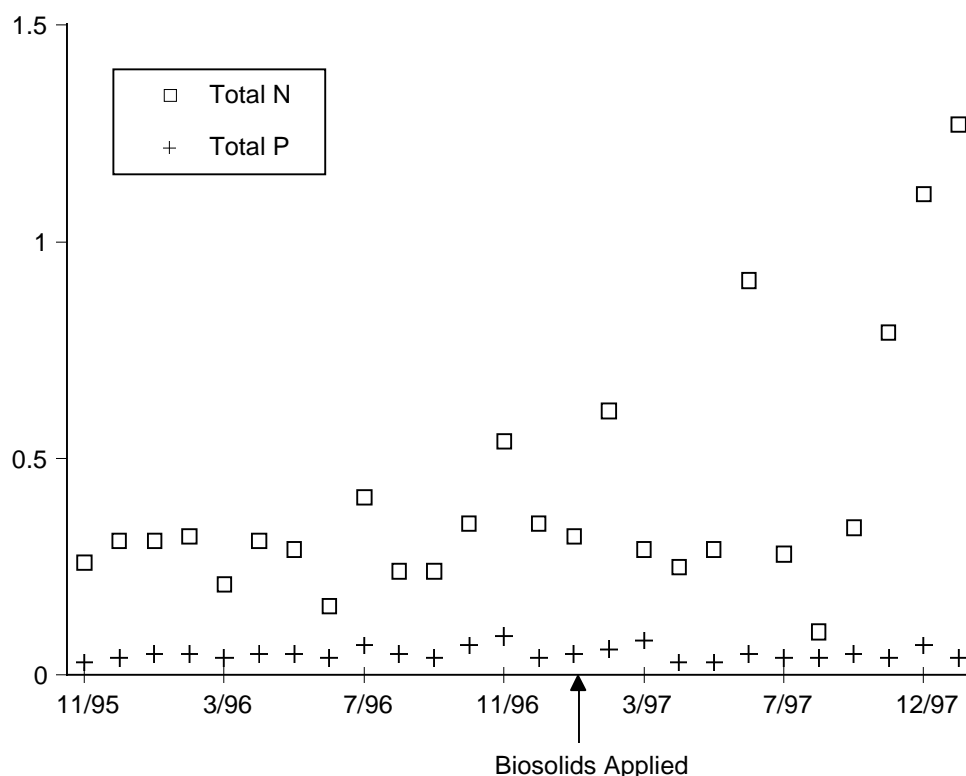
Figure 2. Total N and P in 27 Creek, November 1995 to January 1998.

Storm Runoff Conditions

Several rain storms and ensuing runoff events during 1996–97 and 1997–98 were monitored. Those rainfall events that produced a pronounced rise, peak, and fall of the 27 Creek hydrograph were selected for analysis and water samples removed throughout the hydrograph. Sampling during some runoff events was not done throughout the hydrograph and these cases are noted.

Dissolved Phosphate and BAP

From October 1996 to December 1997, PO_4-P and BAP concentrations showed little to no trends in response to rising or falling 27 Creek hydrographs for several runoff events (Figures 3–7). For brevity, two events prior to biosolids application in autumn 1996 and three events after it are shown. Runoff events in January and March 1997 (Figures 5 and 6) followed biosolids application by one week and two months, respectively; labile P concentrations during these events are equal to or below pre-application levels. Despite sampling primarily the hydrograph rise during the January 1997 event, the results suggest no occurrence of a "first-flush" P runoff effect due to biosolids application. The March 1997 runoff event produced consistent P concentrations over a range of flow rates (Figure 6). A comparison of autumn 1996 events with those of autumn 1997 (Figures 3–4 vs. Figure 7) suggest that biosolids application has done little to change runoff event concentrations of labile P.
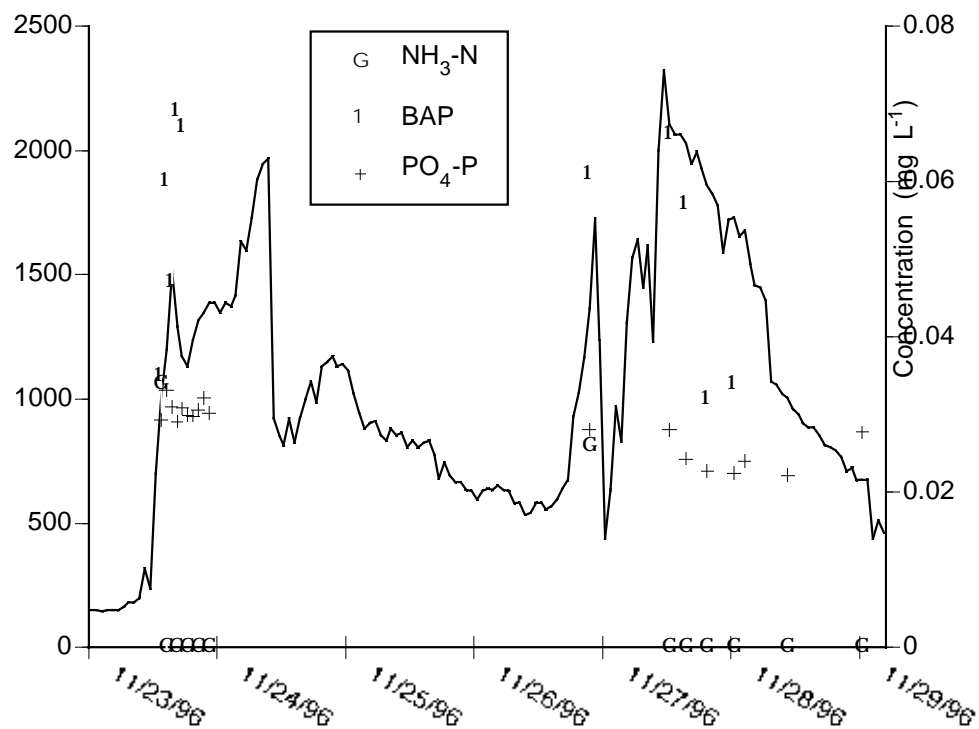
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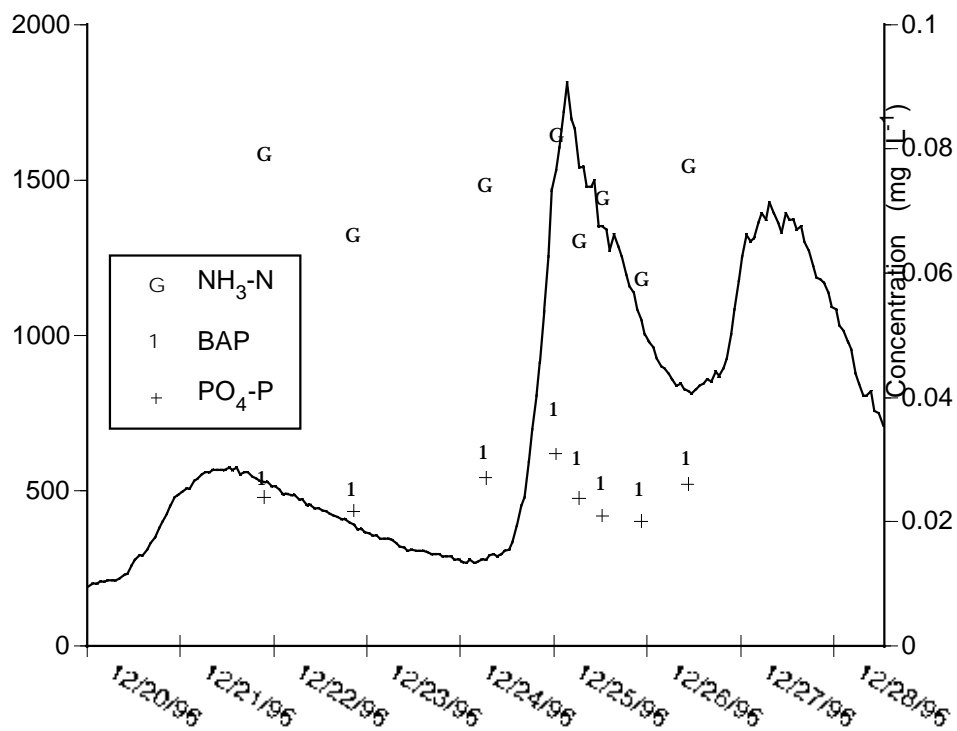Figure 3. Ammonia-N, Phosphate-P and BAP in 27 Creek, November 1996.

Figure 4. Ammonia-N, Phosphate-P and BAP in 27 Creek, December 1996.
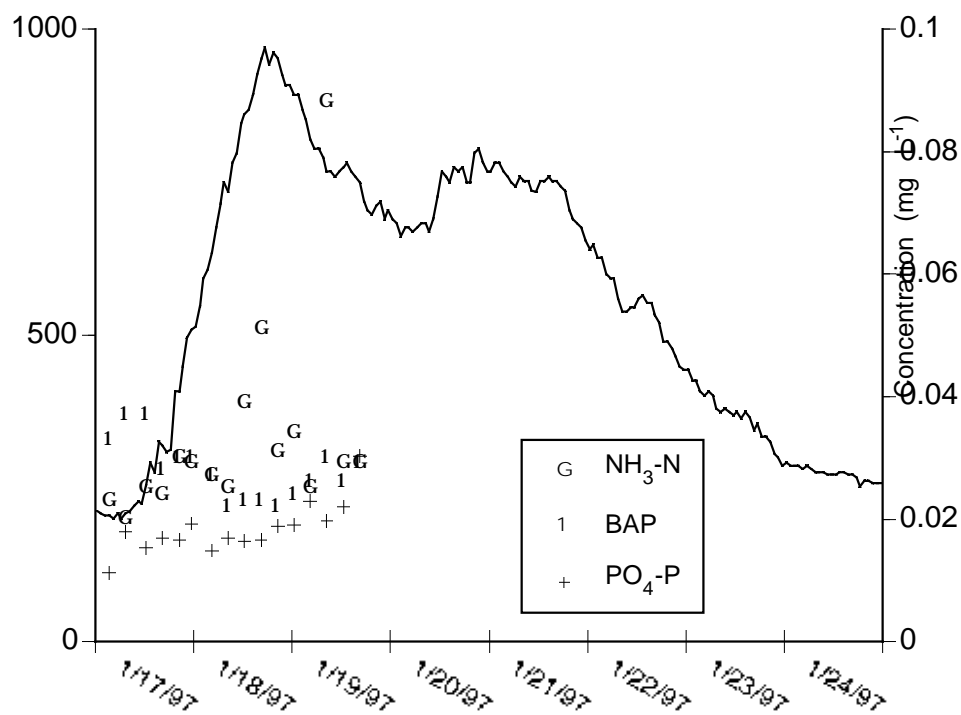
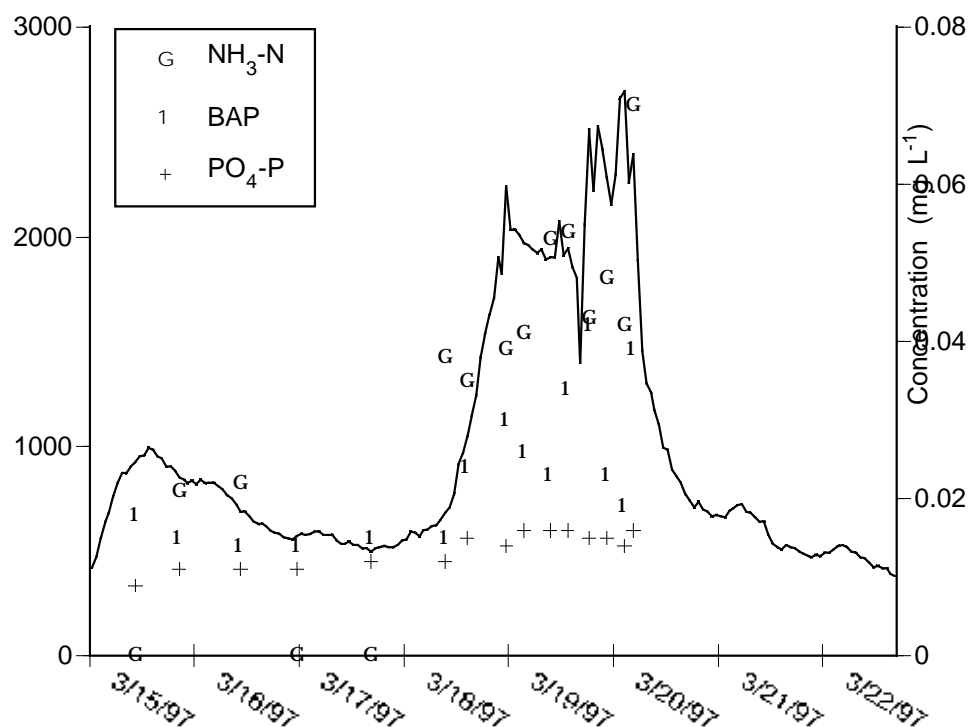Figure 5. Ammonia-N, Phosphate-P and BAP in 27 Creek, January 1997.

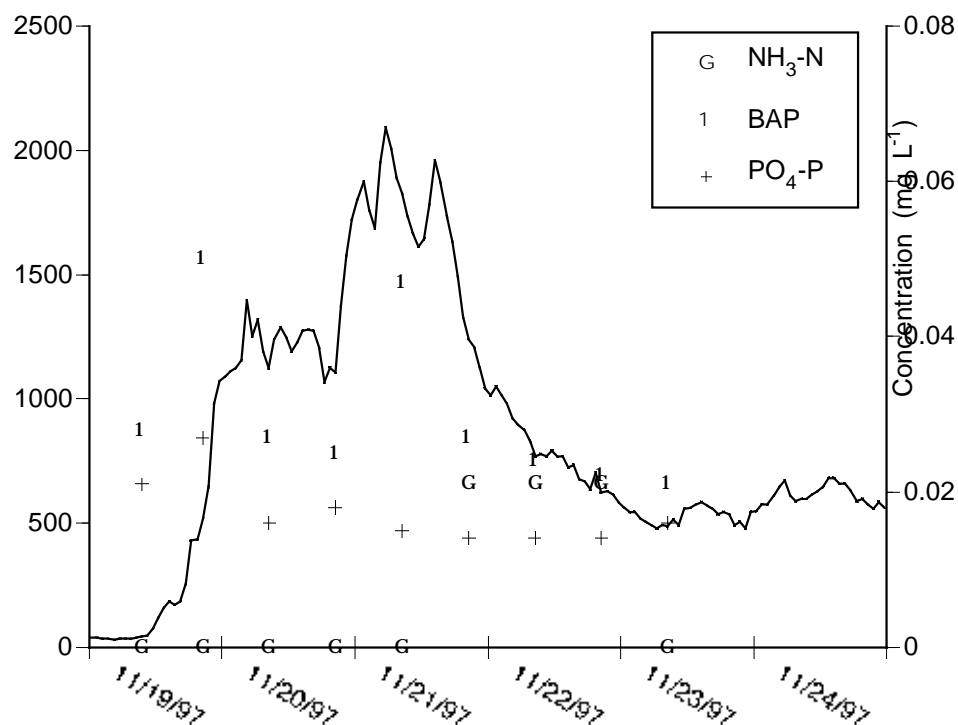Figure 6. Ammonia-N, Phosphate-P and BAP in 27 Creek, March 1997.

Figure 7. Ammonia-N, Phosphate-P and BAP in 27 Creek, November 1997.

Flow-weighted PO$_4$-P and BAP concentrations in 27 Creek have been consistent over the whole study period as well (Table 2). PO$_4$-P concentrations peaked in early October 1996 at 0.07 mg L^{-1} but dropped markedly after this and remained relatively constant between 0.01 to 0.05 mg L^{-1} over the study period. BAP in 27 Creek reflects a similar, but slightly larger concentration range. Flow-weighted total P concentrations fluctuate, with increased concentrations noted on two occasions after biosolids application. As labile P concentrations have not changed due to biosolids application, an increase in flow-weighted total P concentrations cannot be solely attributed to biosolids application. Organic matter input from the heavily vegetated stream corridor or in- or near-stream sediment P sources cannot be ruled out in contributing to total P in 27 Creek. Consistency in flow-weighted labile P concentrations before and after biosolids application strongly suggest that P transport from biosolids applications does not occur and P applied is conserved within the soil.

Dissolved PO$_4$-P and BAP concentrations fluctuate little during runoff event conditions, suggesting that labile P concentrations are not related to fluctuations in flow rate. In addition, biosolids application appears to have little influence on creek labile P concentrations or in changing the runoff event flow-concentration relationship. To check this assumption, PO$_4$-P and BAP concentrations recorded during runoff events were regressed against the flow rate at the time of sampling using both linear and non-linear regression techniques (Wilkinson, 1992). Analysis of the individual runoff events showed that flow rates explain little of the variation ($r^2 < 0.1$) in creek PO$_4$-P concentrations over the range of flow rates recorded (data not shown). Pooling all of the data and separating pre-application from post-application concentrations gave comparable results (Figures 8 and 9). Data transformation of flow rates and concentrations did not improve correlations.
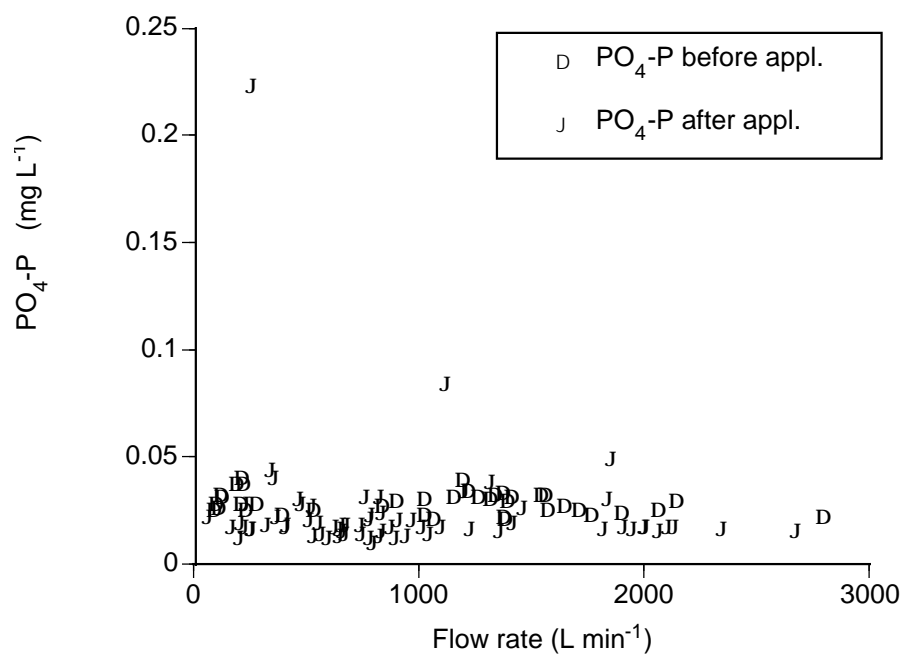
Figure 8. Dissolved phosphate vs. flow rate before and after biosolids application.
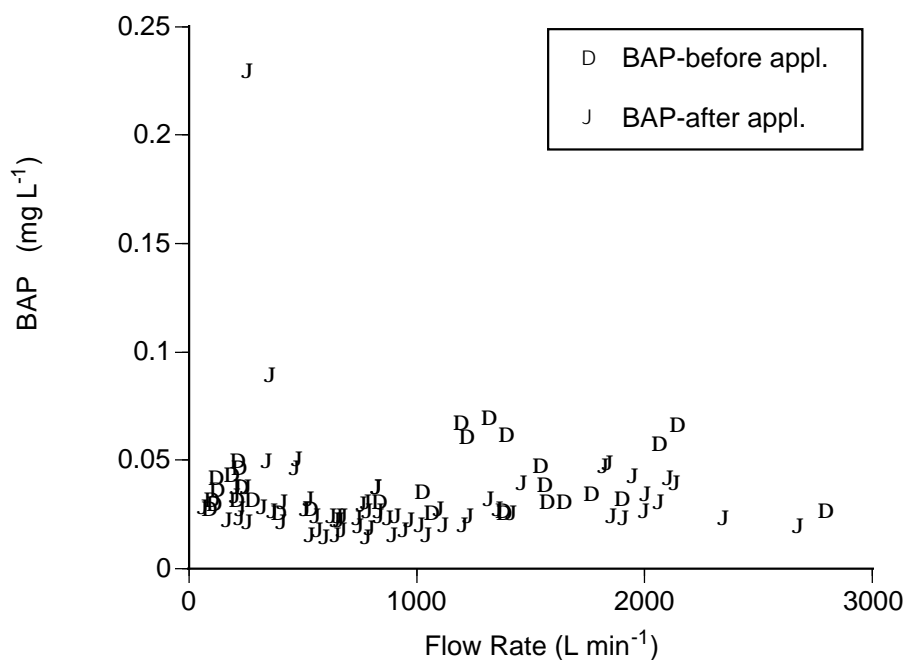

Figure 9. BAP vs. flow rate before and after biosolids application.

Ammonia and Nitrate

Flow-weighted ammonia-N (NH_3-N) concentrations, when detected, were low, averaging between 0.01 and 0.07 mg L^{-1} (Table 2).

Table 2. Average flow-weighted nutrient concentrations (nr = not recorded;. b = before application.

Runoff Event	PO_4-P	BAP	Total P	NH_3-N	NO_3^--N
	mg L^{-1}				
10/17–19/96b	0.03	nr	nr	nr	nr
10/23–25/96b	0.03	nr	nr	nr	nr
11/7–8/96b	0.03	0.03	0.05	nr	0.25
11/13–15/96b	0.03	0.04	0.08	nr	0.35
11/26–28/96b	0.03	0.05	nr	nr	0.35
12/20–28/96b	0.02	0.03	nr	0.07	0.23
12/31/96–1/3/97b	0.03	0.03	0.05	0.07	0.23
1/17–24/97	0.02	0.03	nr	0.04	0.21
3/15–3/22/97	0.01	0.03	0.09	0.04	0.18
5/31–6/4/97	0.04	0.05	0.32	0.07	0.27
10/31/–11/4/97	0.02	0.02	0.05	0.01	0.94
11/19–23/97	0.02	0.03	0.07	0.01	0.97
12/12–15/97	0.05	0.03	0.08	0.04	0.98
1/14–20/98	0.01	0.03	0.13	0.01	1.30

In approximately 40% of water samples taken for this study, ammonia concentrations have been below analytical detection limits (0.01 mg L^{-1}). During runoff events (Figures 3–7), NH_3-N concentrations generally fluctuate with changes in flow rate; some storms produced an apparent concentration-flow relationship. However, regression analysis of pooled NH_3-N data shows that flow rates are not a good predictor of NH_3-N concentrations in 27 Creek (Figure 10).

Ammonia-N concentrations in freshly applied biosolids are relatively high, ranging from 0.5 to 1.5% on a dry weight basis. Consequently, runoff waters directly contacting and moving through biosolids would be susceptible to high NH_4^+-N concentrations immediately after biosolids application. Conversely, NO_3^--N concentrations in anaerobically digested biosolids are often below 50 mg kg^{-1}. Therefore, in assessing changes in 27 Creek water quality, NH_3-N is a useful early indicator of possible effects of biosolids application on water quality, while NO_3^--N is useful over the long-term as biosolids decomposes and N mineralizes.

In the 1996–97 monitoring period, flow-weighted average NO_3^--N concentrations during runoff events were consistent, ranging between 0.18 and 0.35 mg L^{-1} (Table 2). This concentration range generally mirrors that found in precipitation (NADP, 1998). The five year (1992–96) average annual volume-weighted mean NO_3^--N concentration in precipitation is 0.34 mg L^{-1}. As with P, the highest concentrations noted in 27 Creek during the first year of runoff monitoring were recorded during October and November 1996 runoff events. Runoff event NO_3^--N concentrations fluctuated between 0.2 and 1.5 mg L^{-1} over the entire study period and generally no relationship was observed between flow rates and NO_3^--N concentrations (Figure 11).
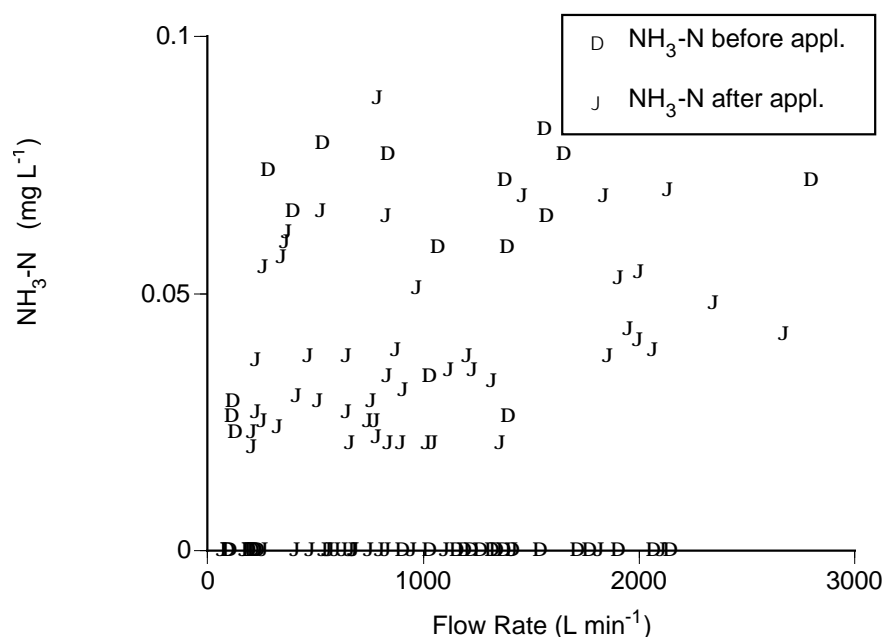
Figure 10. Ammonia-N vs. flow rate before and after biosolids application.
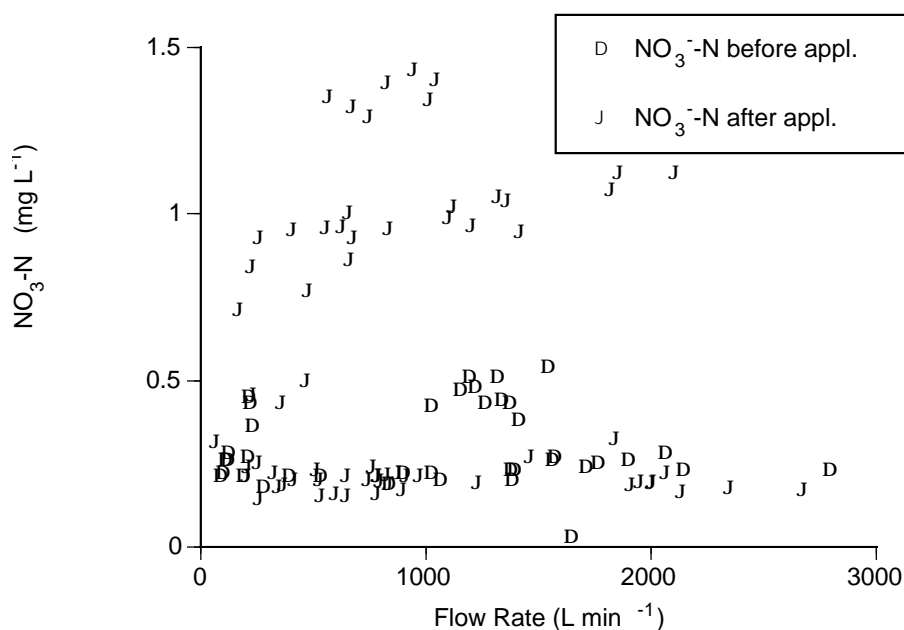

Figure 11. Nitrate-N vs. flow rate before and after biosolids application.

Beginning in late October 1997, the average flow-weighted NO_3^--N concentration noticeably increased to approximately 1 mg L^{-1} (Table 2). This is likely an effect of biosolids in increasing the soil-water NO_3^--N concentration due to organic matter and biosolids decomposition and N mineralization within the 27 Creek watershed. Nitrate-N concentrations in 27 Creek are well below drinking water standards, however. In general, NO_3^--N concentrations are greatest during late autumn months. This seasonal pattern of elevated nutrient concentrations during fall months is consistent with results from other watershed studies in the Pacific Northwest and British Columbia, and is often most pronounced for NO_3^--N (Edmonds et al., 1995; Feller, 1979).

Watershed Outputs of P and N

Watershed export of phosphorus and nitrogen for individual runoff events was determined by multiplying flow-weighted storm runoff event concentrations by the runoff volume. This value was then divided by the total watershed area and duration of the storm event to give an estimate of nutrient export on a g ha^{-1} day^{-1} basis. Table 3 shows the watershed export of nutrients for fourteen runoff events between October 1996 and January 1998.

Mass export of PO$_4$-P and BAP has been consistent over the two-year study period and there appears to be no effect of biosolids application on daily export during runoff events. In general, export of labile P forms is greatest in autumn and early winter, presumably due to decomposition following leaf and litter drop and subsequent mineralization of organic P. Pre-application runoff event nutrient mass export for PO$_4$-P and BAP peaked in November 1996 and declined two- and three-fold, respectively, before application. Peak export rates after application were noted in December 1997 for PO$_4$-P and November 1997 for BAP; mass export of both parameters declined in January 1998. The late November and December peaks in nutrient mass export during both monitoring seasons suggest there are seasonal controls on watershed export of labile P forms. Near creek soil and sediment P and organic debris input into the stream likely regulate PO$_4$-P and BAP concentrations in the creek and probably control total P concentrations as well.

Export of total P has increased over the runoff-event monitoring period, but relating the increase in total P export solely to biosolids may not be warranted. For example, PO$_4$-P and BAP export have been consistent over the monitoring period and no clear-cut effect of biosolids on export of either parameter has been noted. As BAP is a measure of labile P, the difference between it and total P suggests that resistant organic debris or sediments are contributing to the total P load in 27 Creek. The creek corridor is heavily laden with organic debris and deciduous and evergreen plants and this may explain some of the variation in total P export.

Table 3. 27 Creek watershed nutrient export (nr = not recorded; b = before application).

Runoff Event	PO$_4$-P	BAP	Total P	NH$_3$-N	NO$_3^-$-N
	g ha^{-1} day^{-1}				
10/17–19/96b	0.1	nr	nr	nr	nr
10/23–25/96b	0.2	nr	nr	nr	nr
11/7–8/96b	0.2	0.2	0.4	nr	2
11/13–15/96b	0.5	0.6	1.3	nr	5
11/26–28/96b	2.2	4.0	nr	nr	27
12/20–28/96b	0.8	1.0	nr	2.3	7
12/31/96–1/3/97b	1.2	1.5	2.3	3.6	11
1/17–24/97	0.9	1.2	2.8	1.6	9
3/15–3/22/97	0.9	1.7	5.7	2.7	12
5/31–6/4/97	1.1	1.6	9.5	2.0	8
10/31/–11/4/97	0.3	0.5	0.9	0.03	19
11/19–23/97	1.1	2.1	4.9	0.6	66
12/12–15/97	2.7	nr	4.5	2.1	56
1/14–20/98	0.7	1.3	6.9	0.3	67

The nitrogen data show contrasting trends. Ammonia-N export has been steady over two monitoring seasons, suggesting that direct runoff from biosolids into receiving waters does not occur. In addition, the stable export rates along with a weak relationship between flow rate and NH_3-N concentration suggest that near-stream sources of NH_3-N influence stream concentrations and thus export. Ammonia-N export rates are highest in autumn months and during large runoff events (12/96 and 3/97). Peak NO_3^--N export occurred 11 months after biosolids application and was double the peak export before application. Biosolids elevate soil NO_3^--N levels as expected, and combined with seasonal increases in soil NO_3^--N, substantially increases export during autumn–winter runoff events.

Consistent flow-weighted labile P and ammonia-N concentrations and export on a g ha^{-1} day^{-1} basis in 27 Creek suggest that direct runoff from biosolids into receiving waters does not occur using modern application technologies and proper stream and ephemeral drainage buffering techniques. Large runoff events do not appear to change the pattern or amount of labile P or ammonia-N leaving the watershed. Seasonal effects such as changes in soil nutrient status due to organic matter decomposition and mineralization and creek corridor vegetation/sediment dynamics cannot be excluded as factors affecting 27 Creek nutrient concentrations or watershed mass export.

Conclusions

- Little relationship exists between 27 Creek flow rates and P or N concentrations.

- Flow-weighted concentrations of PO_4-P and BAP have been relatively constant over the study period, suggesting no effect from biosolids on Creek labile P. NH_3-N behaves similarly, with flow-weighted concentrations ranging from below detection limits to 0.07 mg L^{-1}.

- Flow weighted NO_3^--N concentrations noticeably increased after biosolids application. Nitrate-N concentrations recorded, however, are well below drinking water standards (<10 mg L^{-1}) and are typically below 1 mg L^{-1}.

- Peak mass export rates of PO_4-P and BAP were noted in autumn months with a general two-fold decline during winter and spring runoff events. Biosolids appears to have little effect on export rates of labile P. Total P export during runoff events has generally increased over the study.

- Ammonia-N export does not appear to be affected by biosolids application. Export was generally greatest in winter months.

- Peak NO_3^--N export occurred following biosolids application and was approximately two-fold greater than peak pre-application autumn export.

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